

# Final Report

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## **Boltzmann Transport Code Update: Parallelization and Integrated Design Updates**

For the period July 2000 to July 2003

By

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## **Parallelization**

The on going efforts at developing a web site for radiation analysis is expected to result in an increased usage of the High Charge and Energy Transport Code HZETRN. It would be nice to be able to do the requested calculations quickly and efficiently. Therefore the question arose, "Could the implementation of parallel processing speed up the calculations required?" To answer this question two modifications of the HZETRN computer code were created. The first modification selected the shield material of Al(2219) , then polyethylene and then Al(2219). The modified Fortran code was labeled ISSTRN.F. The second modification considered the shield material of CO<sub>2</sub> and Martian regolith. This modified Fortran code was labeled MARSTRN.F.

The Message Passing Interface MPI-programming language was utilized. This is a Fortran language group of code statements with approximately 125 MPI programming instructions available for parallel programming purposes. Various test MPI programs were then created and run on parallel computers in order to test the MPI programming statements necessary for the modification of the ISSTRN.F and MARSTRN.F computer codes to run in a parallel environment. The MPI programming was then woven into the above codes to test the feasibility of implementing radiation programs using a parallel platform and to test the run times associated with these modifications. The question to answer is "How much computer run time reduction is there in moving codes to a parallel environment?" The computers used were the ODU SUN Starfire HPC 10000 system with 64 processors, each running at 325MHZ, and the NASA SGI Whitcomb computer with 16 processors, running at 500MHZ. A total of nine test programs have been created. The test programs were used to develop a parallel implementation of the MARSTRN.F computer code for neutron radiation fluence on the Mars surface. In addition we developed a parallel implementation of the ISSTRN.F computer code for neutron radiation in an International Space Station environment. The MARSTRN.F and ISSTRN.F codes have two switches labeled IGCR and ISCR for inclusion of galactic cosmic rays and solar particle events. These switches are either on (1) or off (0) and greatly affect the computer run time of the codes.

The above codes were run in both a serial and parallel modes in order to compare the computational times. The Table 1. illustrates the run times of these codes.

The bar chart is the same information of run times represented in graphical form. This illustrates that all things being equivalent, then the parallel codes will run faster by anywhere from a factor of two to a factor of six. The run times are affected by many factors.

The bottom line is "How much money do you have to spend?" The parallel computers were all low cost machines, placed in a parallel configuration. For the same price of many low MHZ computers one can purchase a single high MHZ fast serial computer which can perform the same task in the same amount of time. This is just one of many factors which affect the decision making process of computer purchases.

1	ODU SUN HP10000 Computer	Marstrm code	serial run IGCR=0, ISCR=1	6.54 hours
	ODU SUN HP10000 Computer	Marstrm code	parallel run IGCR=0, ISCR=1	1.081 hours
2	ODU SUN HP10000 Computer	Marstrm code	serial run IGCR=1, ISCR=1	22.646 hours
	ODU SUN HP10000 Computer	Marstrm code	parallel run IGCR=1, ISCR=1	3.7 hours
3	ODU SUN HP10000 Computer	Issrm code	serial run IGCR=1, ISCR=1	12 hours
	ODU SUN HP10000 Computer	Issrm code	parallel run IGCR=1, ISCR=1	4.6 hours
4	NASA Barb SGI Computer	Issrm code	serial run IGCR=1, ISCR=1	7.22 hours
	NASA Barb SGI Computer	Issrm code	parallel run IGCR=1, ISCR=1	4.00 hours

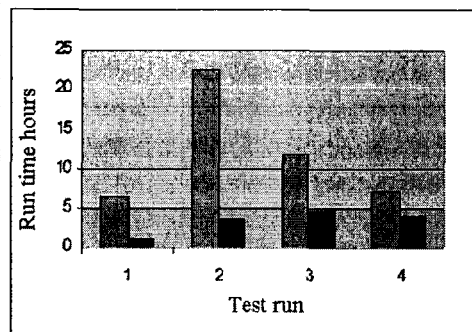


Table 1. Comparison of computer run times

## Introductory Computational Overview

An important part of the general grant activities of developing and implementing high-speed computational techniques (with emphasis on parallel processing) includes development of supporting algorithms that are efficient and readily adaptable to incorporation as sub-programs in a larger framework of computer analysis systems. The formulation of such sub-programs that focus on specific applications pertinent to aspects of space radiation effects has constituted the principal activity of John Nealy. In most cases, the various sub-programs have been created with a view toward implementation as both "stand-alone" procedures as well as modules integrated into larger general analysis systems.

The following sections summarize contributions made by J. Nealy during the course of the grant period (July 2000 – July 2003) . His contributions can be classified as applications in three special areas of space radiation effects and analysis:

1. High-energy electron transport and effects; code procedures applicable to electrons trapped in the magnetic fields of Earth and Jupiter.
2. Directional (vector) flux of charged particles (electrons, ions) in planetary magnetic fields and their interaction with spacecraft configurations.
3. Implementation of interplanetary region radiation exposure analysis for conceptual missions to Earth-Moon libration point stations and Jovian moon excursions.

In the ensuing descriptions of major aspects of these activities, general references to primary sources of background material are designated as R1, R2, ..., etc.; new documentation of research results generated during the course of specific grant activities are designated as P1, P2, ..., etc.

## **Electron Transport Analysis Activities**

The Continuous-Slowing-Down-Approximation (CSDA) in the one-dimensional (“straight-ahead”) formulation has been shown to be an accurate means of describing transport of protons and heavier nuclei in condensed media (P1; Wilson, et al., 1995). The same approximations, however, are not directly applicable to electron transport due to their susceptibility to multiple scattering and collisional energy fluctuations. Accurate description of electron transport is ordinarily provided by Monte-Carlo techniques that accumulate statistics over many thousands of electron path histories. Such techniques are particularly cumbersome and time-consuming in situations involving repetitive calculations. Thus, a special effort was put forth to formulate an electron transport procedure in which the effects of scattering and energy fluctuations are appropriately parameterized for inclusion in a deterministic (non-statistical), quasi-CSDA approach.

Transport of LEO electrons in condensed materials has been calculated with a deterministic code of recent vintage developed at NASA-Langley (P1; Nealy et al., 2002). An energy dissipation function of the form

$$G(E,t) = \frac{d(\eta W)}{dt}$$

has been used as formulated by Kobetich and Katz (R2; 1969) in which  $G$  is the energy dissipated at distance  $t$  in a material by electrons of initial kinetic energy  $E$ . The residual energy of the electron at  $t$  is  $W$ , and  $\eta$  is a transmission function derived from experiments and parameterized in terms of  $t$  and atomic number. A parameterization is also used for the practical range of electrons in materials (R3; Tabata et al., 1972) which is also based on numerous experiments with a variety of materials (mostly heavy ions). In the course of the code development, a new formulation of the multiple scattering parameterization was generated that provided a more realistic description of scattering effects due to lighter ions. The results of the new formulation are compared to the original version in Fig. 1. Range vs. energy relationships are derived from the range formulas and are used to extract the residual energy according to

$$R_{pr}(W) = R_{pr}(E) - t$$

when the practical range satisfies the condition  $R_{pr}(W) > 0$ . Using the fact that the energy dissipation formulas have been developed in terms of attenuation in a semi-infinite slab for  $2\pi$  steradians, an expression for the electron flux spectrum at a location  $t$  may be written in terms of its initial spectrum and the stopping powers,  $S$ , as

$$\phi(W, t) = (1/2\pi)\phi(E, 0)G(E, t)\frac{S(E)}{[S(W)]^2}$$

Radiation emitted by a charged particle under acceleration or radiation caused by deceleration of charged particles when passing through a field of atomic nuclei is called bremsstrahlung. Radiation emitted by a charged particle passing through a magnetic field is referred to as synchrotron radiation. A part of the general radiation field of decelerating electrons consists of bremsstrahlung photons that also contribute to the resulting energy deposition. The photon source term at a given location may be evaluated from interaction cross sections,  $\sigma(E_v, W)$ , for production of photons of energy  $E_v$  by electrons of energy  $W$ . These cross sections have been extensively tabulated (R4; Seltzer and Berger, 1985) and are incorporated as a database within the electron transport code. This source term is evaluated as

$$\zeta(E_v, W) = \int_{E_v}^{W(t)} \phi(W', t) \sigma(W', E_v) dW'$$

Attenuation of the emitted photons in the material is characterized by an extinction coefficient,  $\mu_T$ , and the photon differential energy spectrum at location  $t$  in the medium may be found from a solution of the radiative transfer equation:

$$\phi(E_v, t) = \int_0^t \zeta(E_v, x) \exp[-\mu_T(t-x)] dx$$

Photon absorption coefficient data used in the present procedure have been taken from the tabulations of Storm and Israel (R5; 1970). The present code formulation assumes all photons generated propagate in the direction of electron motion. Numerous comparisons with Monte Carlo calculations having equivalent input and set-up have been made and all have indicated that for energy spectra typical of trapped electrons in LEO, estimates for electron exposures are not seriously compromised. One such comparison for a typical LEO spectrum normally incident on a water slab is shown in Figure 2. The comparison calculations were performed with the TIGER-P Monte Carlo code (R6; Halbleib et al., 1992).

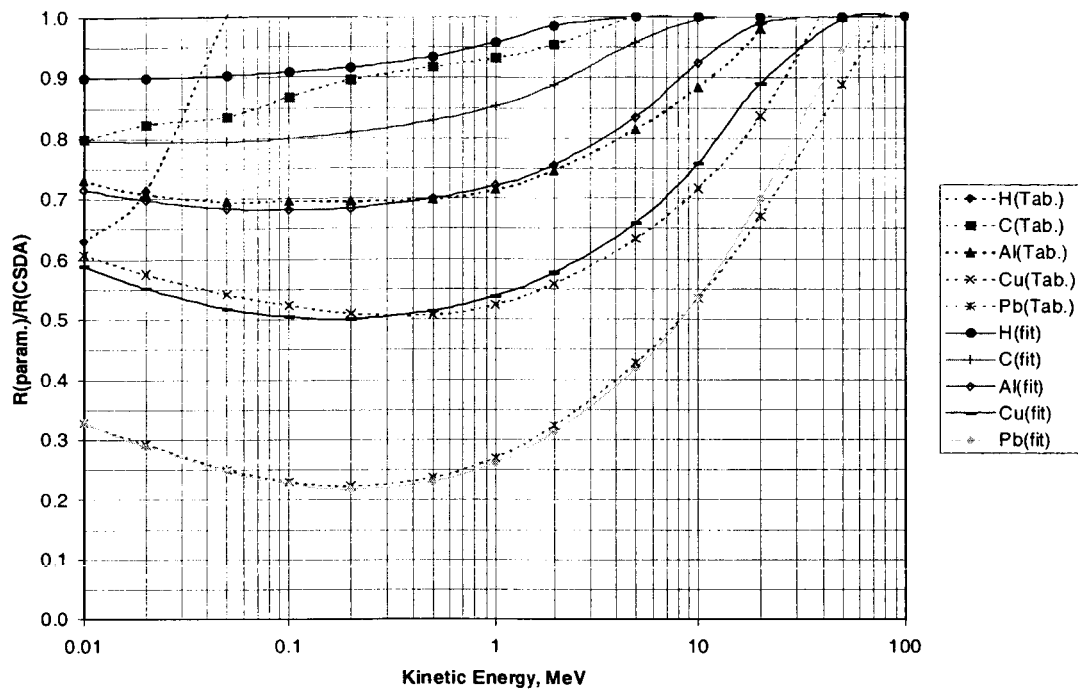


Figure 1. Ratios of parameterized ranges ( $R_{\text{param}}$ ) to CSDA range for selected elemental species. Solid curves are present study curve fits; dashed curves are from Tabata et al., 1972 (Ref. R3).

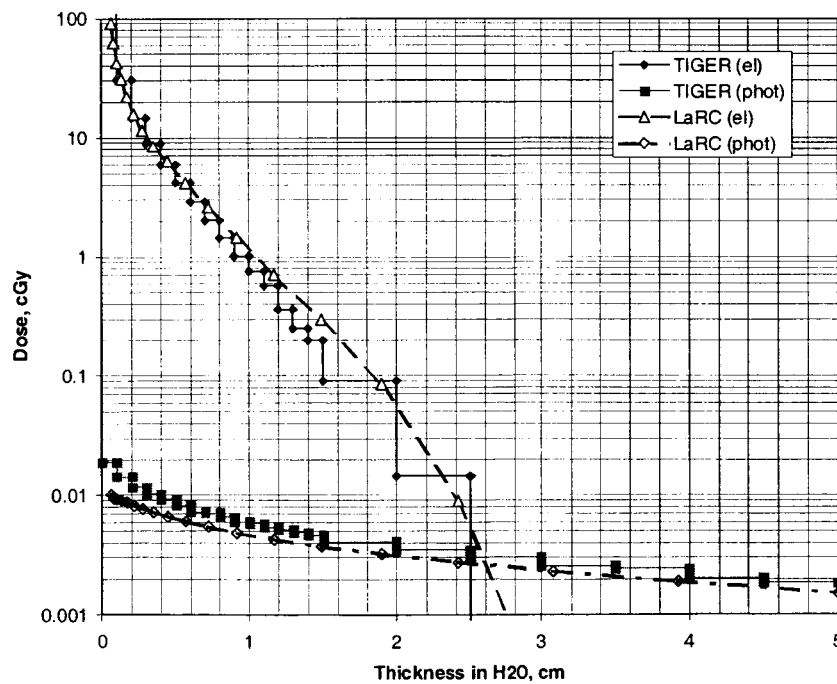


Figure 2. Langley (LaRC) Electron Code results compared to Monte Carlo (TIGER) calculations.

## **Directional Flux Algorithm for Magnetically Trapped Particles**

The preponderant radiation dose incurred by astronauts inside the International Space Station (ISS) arise from the galactic cosmic rays and trapped proton environment in the South Atlantic Anomaly (SAA) region. The trapped particle fluxes in this setting have pronounced directional characteristics since this is a region close to a “mirror point” for the protons trapped in the approximate magnetic dipole field of the earth. Near a mirror point, the spiraling particle paths are nearly normal to the field lines (i. e., pitch angle approaches  $90^\circ$ ). A good account of the theoretical basis for the vector flux of protons in the SAA may be found in Heckman and Nakano (R7; 1969), and computational models have been developed for analyzing the effects of directionality (R8; Watts et al., 1989; and R9; Kern, 1994). Using critical assumptions and approximations, an expression for the directional flux has been found (R7; Heckman and Nakano, 1969) in terms of local magnetic field vector,  $\mathbf{B}$ ; altitude,  $H$ ; ionospheric scale height,  $h_s$ , and the pitch and azimuth angles ( $\theta$  and  $\lambda$ ). This formula, in the nomenclature of Kern (R9; 1994), is expressed as a ratio of the vector flux to the omnidirectional (integrated) value:

$$\frac{J}{J_{4\pi}} = F_N \exp\left[\frac{-(\pi/2 - \theta)^2}{2\sigma_\theta^2}\right] \exp\left[\frac{r_g \cos I \cos \lambda}{h_s}\right]$$

where  $I$  is the magnetic dip angle, and  $r_g$  is the proton gyroradius given by

$$r_g = \frac{\sin \theta \sqrt{E^2 + 1876E}}{30|\mathbf{B}|}$$

with the proton kinetic energy,  $E$ , in MeV and magnetic field strength,  $B$ , in gauss. The standard deviation of pitch angle is given by

$$\sigma_\theta = \sqrt{\frac{h_s}{K \sin I}}$$

where

$$K = (4/3) \frac{R_\oplus + H}{(2 + \cos^2 I) \sin I}$$

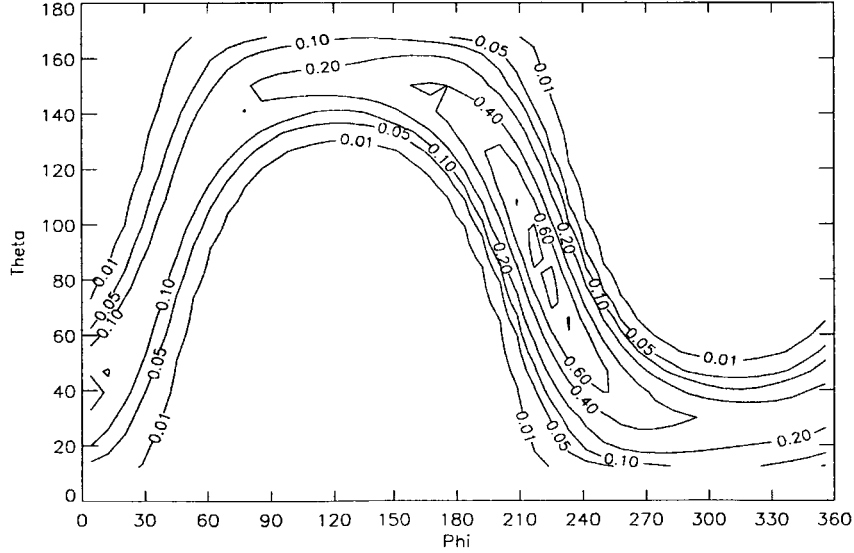
with  $R_\oplus$  representing the earth radius.  $F_N$  is a normalization factor, parameterized by Kern (1994) as:

$$F_N = (.075/\sigma_\theta)(.8533 + x)\exp(-x)$$

where

$$x = \frac{r_g \cos I}{h_s \sin \theta}$$

When the omni-directional flux is redistributed according to the distribution function,  $J/J_{4\pi}$ , a pattern emerges in which most particles are directed in a very pronounced band of zenith and azimuth angles. Figure 3 shows a contour plot of instantaneous relative flux intensity for a location centered in the SAA. The intensity is expressed as a function of spacecraft spherical coordinates (polar angle theta, azimuth angle phi) for which the flight path is commensurate with the ISS moving south to north in its prescribed orbit (400 km, 51.6° inclination). It is often difficult to readily interpret the results of such calculations from tabulated data or even contour plots. The relatively new technologies allowing virtual 3-D immersive visualization provides a means for more rapid and less difficult diagnoses.



**Figure 3. Contour plot of directional flux intensity distribution in vehicle(ISS)-fixed spherical coordinates.**



**Figure 4. Photograph of directional intensity data as spherical dose pattern in CAVE 3-D visualization facility displayed by student researcher at NASA-Langley.**

## **Representative Interplanetary Mission Analysis**

Previously, highly publicized planetary probes (Pioneer, Voyager, Galileo) have revealed the strong intrinsic magnetic field of Jupiter and the associated intense high energy particle fluxes. Recent interest in establishing remote sensors on the surfaces of large natural Jovian satellites (whose orbits are in the high flux region) has generated concern regarding the survivability of electronic instrumentation placed in this harsh environment.

In order to illustrate the versatility of the electron code to a specific application, the exposure due to energetic electrons incident on shielded electronic devices placed on the surface of the Jovian moon Europa has been estimated. A first requirement is the specification of the high energy environment, and as an ancillary task of the grant activity, an algorithm for trapped electron and proton fields in the vicinity of Jupiter has been formulated based on the published model description of Divine and Garrett (R10; 1983). Using this code, the electron flux at the orbital distance of Europa has been calculated (see Fig. 5) and used as input in the electron transport code. Fig. 6 shows the resultant dose vs. depth functions due to incident electrons as a function of scaled shield thickness of candidate materials. An additional dose contribution is provided by photons generated in the shield medium (bremsstrahlung) that is also calculated in the computational procedure, with results shown in Fig. 7. Finally, Fig. 8 shows a plot of shield thickness vs. total dose for the selected materials, and demonstrates the considerable difference in shield effectiveness for the differing substances.

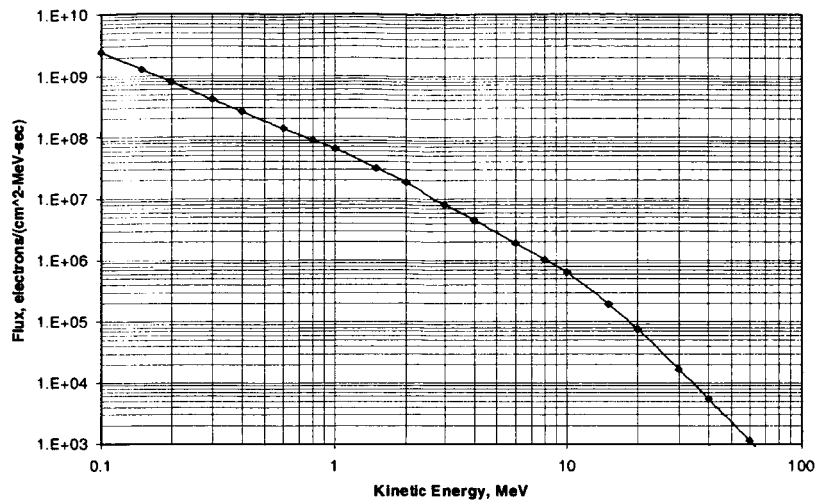


Figure 5. Differential electron flux at Jovian moon Europa.

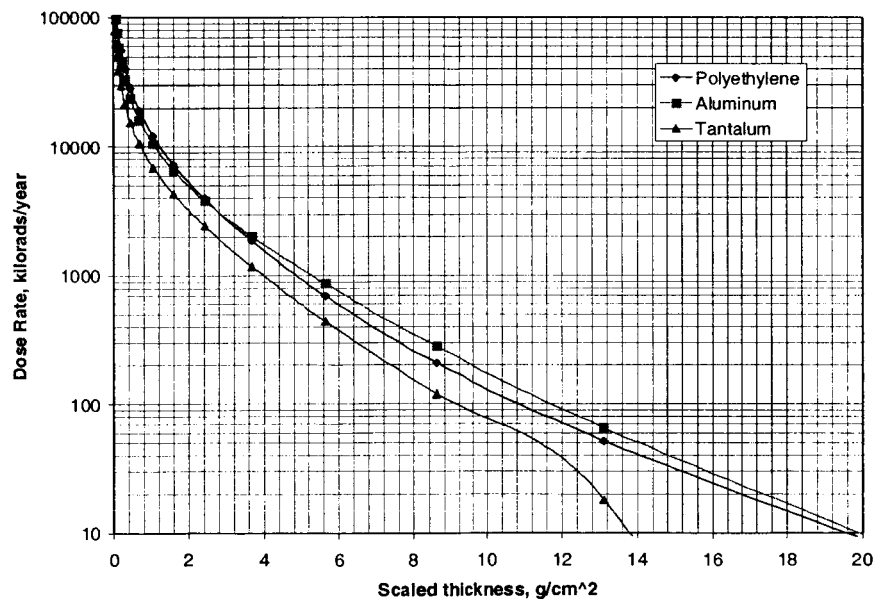


Figure 6. Electron dose vs. scaled thickness for selected materials with Europa electron exposure.

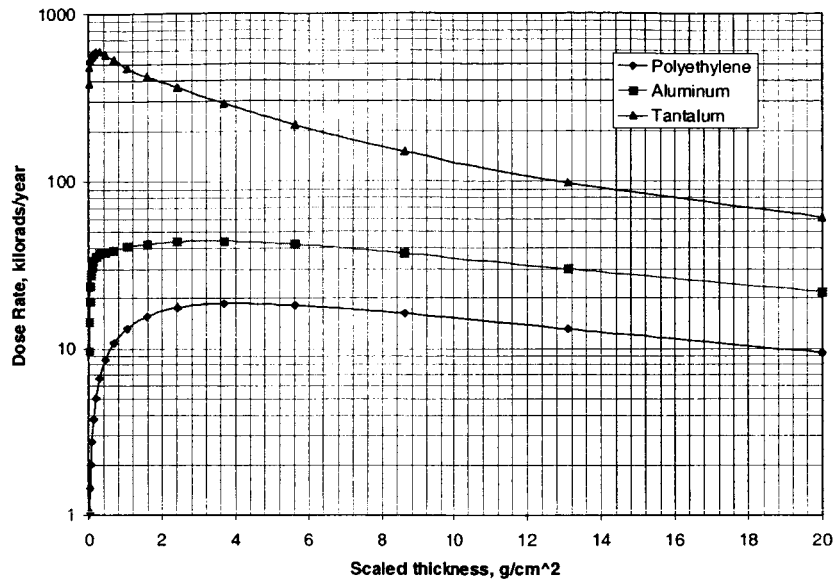


Figure 7. Bremsstrahlung dose vs. scaled thickness for Europa electron exposures.

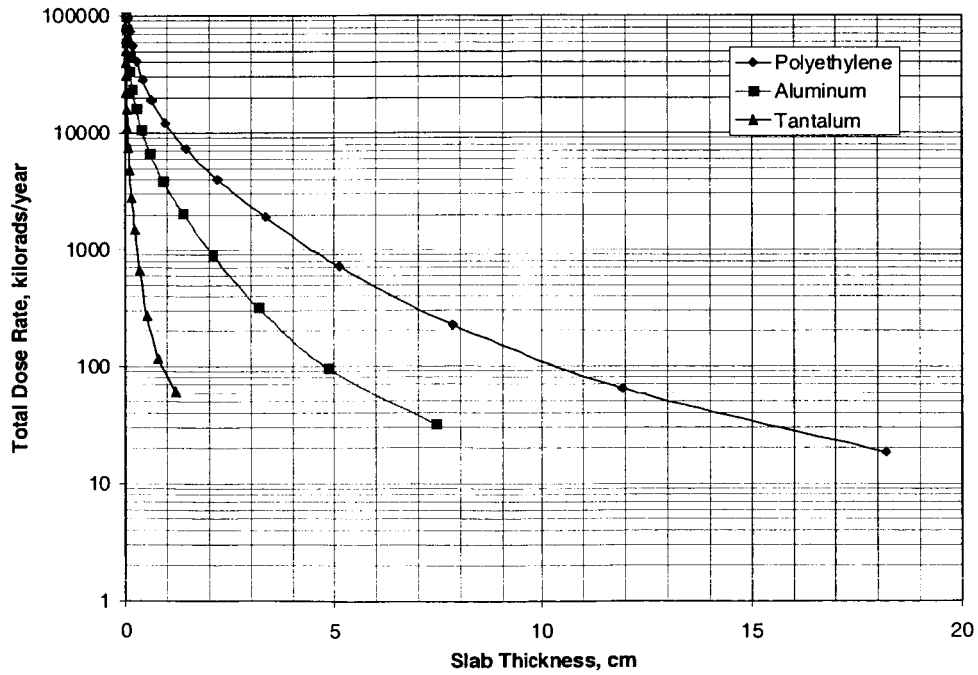


Figure 8. Total dose vs. linear thickness for shield materials in Europa electron flux.

It is readily apparent that dose levels in such an environment are extremely high, and substantial shielding is required for even specially rad-hardened electronics to survive. The advantage of having a rapid-analysis capability is obvious when engineering design must utilize quantitative data in which multiple parameters must be examined for optimum performance.

### **Concluding Remarks**

The foregoing summary is intended to give indication of the approaches and methodologies applied in this part of the grant activities, as well as to convey the generally successful manner in which the research results and products have been applied. A number of additional noteworthy achievements may be mentioned, which include:

*EMU Analyses:* Both electron code and vector flux algorithm have been used extensively in analysis of astronaut exposure during EVA; the codes were integrated into a 3-D visualization system in conjunction with a CAD-modeled EMU (Extravehicular Mobility Unit, or “spacesuit”). (Ref’s P1, P2, P3, P4)

*ISS Analyses:* The codes mentioned previously have also been incorporated in an immersive visualization environment whereby interior exposures within ISS may be calculated and compared with recent and future dosimetric measurements. (Ref’s P5, P6,P7)

*Interplanetary Mission Analyses:* In addition to the Europa scenario described previously, detailed calculations have been performed for long-duration human missions to Earth-Moon libration point L1 and the Jovian moon Callisto. (Ref’s P8, P9)

*Symposia Participation:* Grant team members have actively participated in several major conferences (ICES, STAIF, COSPAR, Space ’03) as well as the annual NASA-DOE Space Radiation Health Investigators’ Workshops (Ref’s P10, P11, P12). At several of these meetings, special interactive demonstrations of the rapid-analysis capabilities were provided.

It is strongly felt by this team member that the overall results obtained from the grant activities have been highly successful and equally rewarding to the participants as well as the recipients.

## **Mathematical Modeling**

Dr. Giovanni De Angelis has been mostly engaged in radiation related mathematical modeling. Most of his activity was devoted to developing space environmental models. As for Earth-related activities, he collaborated in developing a routine that allows computing the directional flux of particles of the trapped radiation in the Earth magnetic field from omni-directional flux models, for a more precise determination of the incoming particle direction and therefore of the radiation doses received in different points and directions, taking into account not only the actual structure of the magnetic field but also that of the Earth atmosphere, with the inclusion of a time-dependent LEO trapped radiation model, taking into account the time variations of the Earth magnetic field as well as of the atmosphere, to calculate both time-dependent particle fluxes and particle lifetimes.

The geomagnetic environment is being further refined with the inclusion of a new routine allowing the evaluation of the directional properties of the cutoff operated by the field on the incoming particles. The reason for doing this is that the shape of the geomagnetic field is such that both a strong latitude effect and a strong angular dependence in its particle shielding properties are present, along with strong time dependencies. The usually used vertical cutoff rigidity does not consider the direction of particle incidence, so the geomagnetic shielding effects on particles with a non-vertical incoming direction are not properly evaluated. For any code aimed at evaluating the radiation dose taken at each location, knowing which particles from any possible direction of incidence may actually contribute to the dose accumulation, is of paramount importance. By considering the departure of the geomagnetic field from a simple dipole representation, the proposed geomagnetic cutoff model allows calculating directional geomagnetic cutoff patterns for charged particles as a function of latitude, longitude, incoming particle arrival direction, altitude and time. Incoming particle arrival angles different from vertical can be considered in the calculations, therefore a totally angle-dependent cutoff at any location at any time can be provided. Moreover, lower energy cosmic rays than in the currently used vertical cutoff models will be allowed to contribute to the dose when coming from the directions of lower cutoff rigidity.

The terrestrial atmospheric ionizing radiation environment has also been considered. Modeling of the evaluation of radiation doses at civilian airline aircraft altitude, to be used in studies about radiation exposure of flight personnel and health outcomes possibly related to previous chronic radiation exposure due to their work activity has been investigated. Dr. De Angelis is continuing his work on the Italian civilian aviation flight personnel, and has been called to obtain doses for Icelandic companies. He obtained data of flight timetables and flight route time and geographical profiles, from which he is reconstructing the doses for each flight leg then to be associated with individual crewmember work history as well as to build averaged parameters for an easier result analysis. He is also working at the development of an improved radiation code to obtain particle fluxes at different locations and depths in the Earth atmosphere: a new Atmospheric Ionizing Radiation (AIR) model is currently being developed for use in radiation dose evaluation in epidemiological studies targeted to atmospheric flight

personnel such as civilian airlines crewmembers. The model will allow computing values for biologically relevant parameters, e.g. dose equivalent and effective dose, for individual flights from 1945. Each flight is described by its actual three-dimensional flight profile, i.e. geographic coordinates and altitudes varying with time. Solar modulated primary particles are filtered with a new analytical fully angular dependent geomagnetic cutoff rigidity model, as a function of latitude, longitude, arrival direction, altitude and time. The particle transport results have been obtained with a technique based on the three-dimensional Monte Carlo transport code FLUKA, with a special procedure to deal with HZE particles. Particle fluxes are transformed into dose-related quantities and then integrated all along the flight path to obtain the overall flight dose. Preliminary validations of the particle transport technique using data from the AIR Project ER-2 flight campaign of measurements are quite encouraging.

Other radiation research activity has dealt with the Moon. The research activity was two-fold: the evaluation of the lunar radiation environment and analysis of future lunar habitats and mission scenarios. An analysis of the radiation safety issues of lunar lava tubes as potential habitats has been performed. Lava tubes are basically formed when an active low viscosity lava flow develops a continuous and hard crust due to radiative cooling of its outermost part, which thickens and forms a solid roof above the still flowing lava stream. At the end of the extrusion period, if the lava flow conditions were ideal in terms of viscosity, temperature, supply rate and velocity, an empty flow channel now free from molten magma is left in the form of an approximately cylindrical-shape tunnel below the surface. Lava tubes are commonly observed on the Earth on basaltic volcanic terrains like those of Hawaii, Oregon and Washington states, with typical sizes of the order of 1-2 km of length, and few meters for cross-sectional parameters (i.e. height and width). Under lunar conditions (lower gravity field, absence of atmosphere), lava channels and tubes are at least an order of magnitude larger in each size dimension, i.e. hundreds of meters wide by hundred of meters or more deep and tenths of kilometers long. For a long time it has been suggested that these natural cavities on the Moon could provide an ideal location for a manned lunar base, by providing shelter from various natural hazards, such as cosmic ray radiation, solar particle events, meteorites, micrometeorites impacts, and impact crater ejecta for example, and also providing a natural environmental control, with a nearly constant temperature of  $-20^{\circ}\text{C}$  unlike that of the lunar surface showing extreme variation in its diurnal cycle.

The analysis performed in this study is limited to the radiation-related properties of the environment, and so an assessment of the lunar lava tube radiation environment and an evaluation of the actual radiation safety features has been demonstrated. As for lunar mission scenarios, an optimization technique has been used to minimize the astronaut radiation exposure and at the same time control the effect of shielding, in terms of mass addition and material choice, as a mission cost driver. The optimization process performs minimization of mass along all phases of a mission scenario, considered in terms of time frame, equipment, location, crew characteristics and performance required, radiation exposure annual and career limit constraints (those proposed in NCRP 132), and implementation of the ALARA principle.

On the lunar surface the most important contribution to radiation exposure is given by background Galactic Cosmic Rays (GCR) particles, and by locally induced particles, mostly neutrons, generated by interaction between GCR and surface material. In this environment manned habitats are to host future crews involved in the construction and/or in the utilization of moon based infrastructure. Four different kinds of lunar missions are considered in the analysis, Moon Base Construction Phase, during which astronauts are on the surface just to build an outpost for future resident crews, Moon Base Outpost Phase, during which astronaut crews are resident but continuing exploration and installation activities, and Moon Base Routine Phase, with shifting resident crews, and Lunar Lava Tubes Habitats.

Deep space missions have been another important research topic for Dr. De Angelis. As for the planet Mars, he developed a new model for the radiation environment to be found on the planet Mars due to Galactic Cosmic Rays (GCR). Solar modulated primary particles rescaled for Mars conditions are transported through the Martian atmosphere, with temporal properties modeled with variable timescales, down to the surface, with altitude and backscattering patterns taken into account. The Martian atmosphere has been modeled by using the Mars Global Reference Atmospheric Model – version 2001 (Mars-GRAM 2001), based on input data generated as output of the NASA Ames Mars General Circulation Model (MGCM) for the lower atmosphere and the University of Arizona Mars Thermosphere General Circulation Model (MTGCM) for the higher atmosphere. The altitude to compute the atmospheric thickness profile has been determined by using a model for the topography based on the data provided by the Mars Orbiter Laser Altimeter (MOLA) instrument on board the Mars Global Surveyor (MGS) spacecraft. The Mars surface composition has been modeled based on averages over the measurements obtained from orbiting spacecraft and at various landing sites, taking into account the possible volatile inventory (e.g. CO<sub>2</sub> ice, H<sub>2</sub>O ice) along with its time variation throughout the Martian year (e.g. polar caps). Particle transport has been performed with the HZETRN heavy ion code. The Mars Radiation Environment Model has been made available worldwide through the Space Ionizing Radiation Effects and Shielding Tools (SIREST) website, a project of NASA Langley Research Center, developed to provide the scientific and engineering communities with an interactive site containing a variety of environmental models, shield evaluation codes, and radiation response models to allow a thorough assessment of ionizing radiation risk for current and future space missions. Results from this model are being compared with two instruments part of the payload of the Mars Odyssey mission, namely HEND and MARIE.

For further distances from the Sun, an analysis for manned missions targeted to the Jovian system has been performed in the framework of the NASA RASC (Revolutionary Aerospace Systems Concepts) program on Human Exploration beyond Mars. The missions were targeted to the Jupiter satellite Callisto. The mission analysis has been divided into three main phases, namely the interplanetary cruise, the Jupiter orbital insertion, and the surface landing and exploration phases. The interplanetary phase is based on departure from the Earth-Moon L1 point. Interplanetary trajectories based on the use of different propulsion systems have been considered, with resulting overall cruise phase duration varying between two and five years. The Jupiter-approach and the

orbital insertion trajectories are considered in detail, with the spacecraft crossing the Jupiter radiation belts and staying around the landing target. In the surface exploration phase the stay on the Callisto surface is considered. The satellite surface composition has been modeled based on the most recent results from the GALILEO spacecraft. In the transport computations the surface backscattering has been duly taken into account. Particle transport has been performed with the HZETRN heavy ion code for hadrons and with an in-house developed transport code for electrons and bremsstrahlung photons. Galactic Cosmic Rays and Solar Particle Events scenarios have both been considered, and doses compared to dose exposure limits. The analyses proved that for mission durations of the order of some years only male crewmembers aged more than 55 are suitable candidates, due to the radiation hazards only.

Further activities dealt with the computation of chromosomal damage from radiation exposure, modeled as prediction of the frequency of dicentric chromosomal aberrations in human lymphocytes. Astronauts after long-duration exposures to space radiation in Low Earth Orbit (LEO) exhibit an elevated frequency of dicentric chromosomes (DIC) in their peripheral lymphocytes. Within the still substantial range of uncertainties regarding the relative biological effectiveness (RBE) of the numerous radiation qualities present in the space radiation field, the observed frequency of DIC is compatible with that expected from the doses of low- and high-LET radiation to which astronauts were exposed in LEO. Extrapolating these findings to long term space exploration missions outside the geomagnetic shielding, the data, along with estimates of radiation exposure during flight, show that the expected frequency of DIC in astronauts lymphocytes will be 10 to 40 times higher than the terrestrial control levels, the variation being dependent on the unpredictable radiation doses received from stochastic solar particle irradiation. This result even applies after a 'heavily' shielded Mars mission. For such long exposures, the concomitant decay during the exposure of DIC frequencies due to removal of lymphocytes carrying DIC has to be taken into account.

The above type of calculation can be applied to other populations exposed to ionizing radiation such as civil aviation flight personnel, the most highly exposed group of professionally exposed workers. As typical examples, the time profiles of frequency of DIC in lymphocytes have been obtained for a pilot, and for a male and a female cabin attendant, whose professional radiation exposures were calculated along the actual flight routes flown during their entire flight career, as recorded in their fictitious duty logs. A typical career pattern of a pilot is that during the first years he serves as a co-pilot on intercontinental flights, then as a first pilot he first serves on short haul flights, i.e. domestic and inner-European flights, and then on intercontinental flights. The frequency of DIC rises during the co-pilot activity time, decays to nearly control values during the inner-European flights, and rises again during subsequent intercontinental flights as captain. Similar effects were observed with the male cabin attendant. For the female cabin attendant, an out-of-work time during a 3-year "maternity leave" can be recognized as a fall in the frequency of DIC. These results demonstrate that experimental epidemiological studies concerning DIC in flight personnel must explicitly take into consideration the exposure time profiles in the prospective study population, and that the

point in time at which blood samples are to be drawn must be selected accordingly. Experimental studies of this kind on the DIC time profiles in suitable populations would be useful to test whether our theoretical computations are correct, and, in particular, whether the numerical values adopted for the various intrinsic model parameters are appropriate. It would especially be interesting to plan and perform such types of studies with astronauts flying to the moon and paving the way to colonize it.

Dr. Giovanni De Angelis has been selected in 2001 as an Expert by the European Commission for the evaluation of radiation doses and past and present flight personnel exposures onboard the aircraft of Icelandair, the national airline of Iceland, for the Icelandic government. He served as a Co-Chairman in the Space Radiation shielding Technology Workshop, held in Hampton VA in April 2002. He has been selected as the Deputy Scientific Organizer of the session devoted to 'Radiation Fields at Aircraft Altitudes' for the 34<sup>th</sup> COSPAR scientific assembly held in Houston in October 2002, in which he served as a Chairman, in the framework of the World Space Congress. He has been asked to chair the session devoted to Cosmic Radiation (Aircrew and Space) Dosimetry at the IX Neutron Dosimetry Symposium 'NEUDOS' to be held in Delft (The Netherlands) on October 2003. Moreover, he has been selected as the Main Scientific Organizer of the session devoted to 'Planetary and Interplanetary Environmental Models for Radiation Analysis' and as the Deputy Scientific Organizer of the session devoted to 'Radiation Fields at Aircraft Altitudes' for the 35<sup>th</sup> COSPAR scientific assembly to be held in Paris (France) in July 2004. Moreover, he received invitations to take part to national and international conferences all over the world.

## **Ph.D. Dissertation**

Graduate student Gary A. Feldman has completed the requirements for a Doctor of Philosophy degree in Computational and Applied Mathematics from Old Dominion University. Research for his dissertation was funded under NASA grant NCC 1-404. His thesis title is:

**A Forward-Backward Fluence Model for the  
Low Energy Neutron Boltzmann Equation.**

Mr. Feldman has graduated in August 2003.

## **Publications and Presentations resulting from NCC-1-404 funding.**

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